BACKGROUND, METHOD, AND ANALYSIS OF RADIATION TESTING FOR COMMERCIAL ELECTRONICS

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Abstract

The use of commercial microelectronics in space can significantly reduce schedule and expense while maximizing speed and performance. Unfortunately, the space environment can significantly reduce the life of commercial products. Testing and analysis can be used to mitigate these risks.

INTRODUCTION

Background

The goal of radiation susceptibility testing is to determine the effects of ionizing radiation on microelectronics. The purpose of testing is to estimate ionizing radiation-induced functional interrupt rates and other error rates that can be expected in space.

The threshold at which damage is caused by energy imparted by the ionization process is most commonly referred to as the Total Ionizing Dose (TID). This dose is a cumulative total of the energy of all of the incident particles causing the device to break down.

Alternatively, atomic displacements within the semiconductor lattice result from Single Event Effects (SEEs) and are not the result of an accumulation of energy from the incident particles. The incident particle dissipates its energy through the excitation of valence electrons as well as elastic collisions with atomic nuclei. The energy imparted to the atomic nuclei may be great enough to displace the atom from its position in the lattice, causing the device to fail.

Single Event Upsets (SEUs) are one of the several types of SEEs and cause the least harm. The two major contributors to SEUs are the trapped protons in the South Atlantic Anomaly (SAA) and heavy ions originating from galactic and solar cosmic rays.

Method

TID testing methods require the device under test to be exposed to low-energy particles until the device accumulates the dose level required to observe errors. This test method is typically long but definitive in determining the TID damage threshold.

SEE testing typically requires the operation of hardware in a high-energy radiation environment, such as a proton stream. Once errors are observed, an analysis is done to make an estimate of the expected error rates. This testing is typically quick as high-energy particles can be used to achieve an accelerated testing profile.

TESTING

To successfully conduct testing and establish the effects of radiation on a device an understanding of available test facilities and potential test methods is required. This section briefly elaborates on potential test facilities and a possible approach to testing.

Facilities

Facilities able to mimic the environment in space are required for testing because the heavy ion and proton flux on Earth is much smaller than is encountered in space. A survey of facilities available for testing electronics that will undergo space flight was completed. The results of the survey are detailed in the attached tables. Table 1 lists some of the accelerators that are being used for heavy ion research. Table 2 lists some facilities that are exclusively proton accelerators. Heavy ion facilities are useful if engineering concerns persist about a devices susceptibility to heavy ions. As detailed in G411-RPT-001, protons make up the great majority of the environment to which most hardware is exposed. Therefore, typically proton testing is sufficient and the approach method discussed below is centered on that approach.

Approach

Semiconductors are the most sensitive of all electronic components to radiation. For most applications

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semiconductor-device performance will determine the maximum radiation flux that an electronic circuit will tolerate. Radiation can cause both permanent and temporary damage to the device. Permanent effects are attributed to bulk damage. The term “bulk damage” is used to describe changes in the properties of structures caused by atomic displacement as a result of exposure to a radiation environment. Temporary effects are generally attributed to the generation of excess free carriers in the junction regions as resulting from exposure to high energy particles.

The most effective way to determine the effects of radiation on microelectronics is through testing the devices in radiation environments.

Several methods exist for conducting radiation testing. Not all of these methods are discussed in detail in this report. References for the omitted methods are given below[1,2,3]. Each method of radiation susceptibility testing requires use of SEU test data, which is measured at a testing facility.

During testing, electronics are exposed to a uniform particle beam to extract failure rate information. A general method for this type of testing is to use the beam test results to determine a failure rate (failures/unit time). The failure rate divided by the particle flux gives the SEE cross section and is usually defined as

$$\sigma_{SEE}(E) = \frac{dN_f}{dt} \cdot \frac{1}{\phi_0},$$

where dN_f/dt is the failure rate, and ϕ_0 is the particle flux. This data can now be used to calculate the soft error rate (SER). To determine the SER, the product of the differential energy flux and SEU cross section are integrated over the energy spectra of interest. The SER is expressed as

$$\frac{dF}{dt} = \int_{E\min}^{E\max} \frac{d\phi(E)}{dE} \sigma_{SEE}(E) dE .$$

This result gives a number of failures per unit time for a given range of particle energies.

For the purpose of data taken, the SER cannot be determined for any energy other than beam energies. Therefore, data taken during testing is reduced statistically using the data from the modeling effort rather than numerically to give an approximate failure rate. This statistical approach can be calculated using the Bendel A method.[4] Efforts have been made by NASA to create computer codes to perform this analysis from test data. [5]

Another method sometimes referred to as the Burst Generation Rate (BGR) method. The BGR method was developed by Ziegler and Lanford [6] to numerically determine the SEU rate induced by proton/neutron interacting with microelectronics. The BGR method hinges on the theory that statistically speaking only the recoil reactions cause upsets. According to the BGR method the SEU rate can be approximated by

$$\frac{dF}{dt_{BGR}} = C \sum_{i}^{N} t \Delta\sigma \int_{Ep} BGR(E_p, E_{ri}) \frac{dJ}{dE} dE_p$$

where C is the collection efficiently, t is the collection depth in µm, $\Delta\sigma_i = \sigma_i - \sigma_{i-1}$ where σ_i is the heavy ion SEU cross section for the i^{th} portion of the curve expressed in cm², $BGR(E_p,E_{ri})$ is the burst generation rate is $cm^2/\mu m^3$, E_p is the energy of the incoming particle in MeV, E_{ri} is the ith recoil energy, (E_{ri} = t ❹ 0.23 ❹ LET_i [MeV]) and dJ/dE is the differential flux in particles/cm²·sec·MeV. [7]

The BGR method is effective for older devices, but does not handle modern devices with smaller sensitive volumes. The method also assumes that the charge collection region is constant, which in actuality it is not. The charge collection region changes dimensions depending on the total deposited energy and location because the depletion region collapses if the energy is sufficiently high. Modern devices have complex charge collection regions because diffused charge in the substrate, well beyond the depletion region, can be collected by a reverse-biased junction. [8]

Another method of testing is to determine the threshold values for both failure modes (permanent and temporary). This test requires a source where the ion species and energies can be changed. Once the threshold is observed experimentally the expected SEU rate can be determined numerically by integrating the fluence from the threshold to infinity. This method has proven to be more costly than the previous method. In general each of these methods is considered a reliable predictor of error rates, but the last method is more valuable to the reliability analysis effort.

RELIABILITY

As stated above data gathered from testing is used to perform analysis to estimate the SEE susceptibility of the device under test. The results collected for a given particle and energy can be used in conjunction with available analysis tools to generate a composite MTBF number due to atomic displacement for a device. In general a failure can be defined as one of the following:

- Single Event Upset (SEU) – an event like a bit flip resulting in a data error only.

- Functional Interrupt (FI) – an event requiring a software reboot or a power cycle.
- Single Event Latchup (SEL) – an event where the device has an abnormal conduction path established by the ionizing radiation and as indicated by a primary power supply current change. Power must be recycled to regain control and/or to save the device from destruction.
- Single Event Burnout (SEB) – an event where the device has an abnormal conduction path established by the ionizing radiation and is destroyed almost immediately.

Microelectronics can experience a reduction in reliability due to TID[9]. A relationship between component life reduction in a transistor is generally given as:

$$\tau_{\Phi} = \tau_o + (1/K_\tau \varphi)$$

Where:

τ_{Φ} is the component life after exposure

τ_o is the component life before exposure

K_τ is the lifetime damage constant (cm^2/particles)

Φ is fluence (particles/cm^2)

Each of the dependant variables can be observed directly through an elaborate test program.

Damage from atomic displacement—as previously discussed—can occur from primary or secondary effects. If a particle enters a material and is of high enough energy to impart recoil energy it will displace an atom by the primary collision and several more through secondary effects. The number of atoms displaced by secondary collisions is given through the equation:

$$N_s(E)=fE/2E_d$$

Where:

$N_s(E)$ is the number of atoms displaced

f is the fraction of recoil atoms energy that will be consumed by ionization

E is the displacement energy

E_d is average over all directions of the displacement energy

This relationship was theorized by Lindhard[10] and has been confirmed experimentally for silicon by Sattler [11].

These atoms create vacancies in the structure which, if not annealed, can cause contamination in materials. It is not known how contamination can effect long term reliability.[12] However, a device that has been recovered through low-temperature annealing, may tend to be more sensitive to further radiation.[13]

There exists a particle of high enough energy to permanently damage microelectronics in an SEE, thereby affecting reliability numbers. Since this particle is undetermined by theory, the reliability numbers cannot be devalued for the purposes of analysis without direct observation during testing.

CONCLUSION

This report details an approach, method and options for using testing combined with analysis and modeling to generate error rates and reliability data for microelectronics based on an operating radiation environment. The data that will be presented in the next report (G411-RPT-003) can be used in conjunction with the test method detailed above and the operations scenarios defined in previously work (G411-RPT-001) to mitigate the effects of radiation on microelectronics.

APPENDIX A – TABLES

Facility	Zproj	Eproj (MeV/nuc)	Eproj(^{56}Fe) (MeV/nuc)
Alternating Gradient Synchrotron (AGS) Brookhaven National Laboratory (BNL) Brookhaven, New York, USA	1–79	600–30K	600–1K
NASA Space Radiation Laboratory (NSRL) Brookhaven National Laboratory Brookhaven, New York, USA	1–79	100–3K	100–1K
Centro Nazionale di Adrotera Oncologica (planned) Italy 88" Cyclotron	1,6	250	—
Lawrence Berkeley National Laboratory Berkeley, California, USA	1–8	55	—
Grand Accelerateur National D'Ions Lourds Caen, France	6–92	25–95	—
Heavy Ion Medical Accelerator at Chiba National Institute for Radiological Sciences (Chiba, Japan)	1–54	100–800	500
Tandem-ALPI Laboratori Nazionali di Legnaro (LNL) Legnaro, Italy	1–8	8–20	—
Superconducting Cyclotron Laboratori Nazionali del Sud (LNS) Catania, Italy	1–6	70	—
ETOILE (2007) Lyon, France	1,6	50–400	—
National Superconducting Cyclotron Lab. Michigan State University East Lansing, Michigan, USA	1–92	90	—
Nuclotron Joint Institute for Nuclear Research (JINR) Dubna, Russia Ring Cyclotron	1–26	6K	6K
Inst. for Physical and Chemical Research Wako Saitama, Japan (Wako Saitama, Japan)	6	137	—
SIS-18 Heavy Ion Synchrotron Gesellschaft für Schwerionenforschung Darmstadt, Germany	1–92	50–2K	1K
Synchrophasotron Joint Institute for Nuclear Research Dubna, Russia	1–16	4K	—

Table 1 - Heavy Charge Particle Accelerators

Facility	E_{max} (MeV)
Brookhaven National Laboratory Linear Accelerator Brookhaven, NY USA	200
Crocker Nuclear Laboratory Cyclotron University of California Davis, California, USA	70
Loma Linda Proton Treatment Center Loma Linda University Medical Center Loma Linda, California USA)	250
iThemba Laboratory for Accelerator-Based Sciences Medical Radiation Group Capetown, South Africa	200
Midwest Proton Radiotherapy Institute Indiana University Cyclotron Facility Bloomington, Indiana, USA	210
Northeast Proton Therapy Center Massachusetts General Hospital Boston, Massachusetts, USA	230
Paul Scherrer Institut Proton Therapy Facility Villigen, Switzerland	270
Proton Medical Research Center University of Tsukuba Tsukuba, Japan	500

Table 2 - Proton-Only Accelerators

APPENDIX B – REFERENCES

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